Published online May 13, 2005



# Seeding Practices and Cultivar Maturity Effects on Simulated Dryland Grain Sorghum Yield

R. L. Baumhardt,* J. A. Tolk, and S. R. Winter


## ABSTRACT

**Typical planting recommendations for dryland grain sorghum [*Sorghum bicolor* (L.) Moench] in the southern High Plains are to delay until soil water is adequate for crop establishment, but no population or cultivar maturity class are specified. Our objectives were to use the SORKAM simulation model, long-term (1958–1998) weather records at Bushland, TX, and known Pullman soil (fine, mixed, superactive, thermic Torrertic Paleustolls) properties to identify an optimum planting date, population, row spacing, and cultivar maturity combination to maximize dryland grain sorghum yield. We simulated sorghum grain yields for combinations of planting dates (15 May, 5 June, and 25 June), populations (3, 6, and 12 plants $m^{-2}$), row spacings (0.38 and 0.76 m), and cultivar maturity class (early, medium, and late). SORKAM consistently ($r^2 = 0.69$, RMSE = 792 kg $ha^{-1}$) simulated grain yields that averaged about 5% more than measured values and correctly simulated row width and population effects on yield. Simulated grain yields increased with narrow row-spacing ~9%, independent of planting date or cultivar. Increasing plant population significantly decreased panicle seed number, seed mass, and plant tillers; however, the simulated grain yield was unchanged (3996–4106 kg $ha^{-1}$) by plant populations. Mean simulated grain yields were greatest for the 5 June planting dates with early and medium maturity cultivars that avoided late summer heat or water deficit stresses and matured before freezing weather. Our results show early or medium maturity cultivars, planted 5 June, in 0.38-m row widths, using 3 or 6 plants $m^{-2}$, achieve the greatest dryland grain yield on a southern High Plains clay loam soil.**


Grain sorghum [*Sorghum bicolor* (L.) Moench] is well adapted to and widely grown on the southern Great Plains. Dryland grain sorghum yields at the USDA-ARS Conservation and Production Research Laboratory, Bushland, TX, have increased 139% from 1600 to 3800 kg $ha^{-1}$ during the years 1956 to 1997 (Unger and Baumhardt, 1999). These grain yield increments were attributed to improved hybrids and management practices that utilize residue to conserve soil water; however, no optimum combination of planting date and population has been determined for the range of cultivar maturity classes grown in this region. For example, the top dryland grain yields recognized in 2003 by the National Grain Sorghum Producers were from fields separated by a distance of <150 km but managed very differently, i.e., planted during late May to early June at populations ranging from 4.5 to 15.8 seed $m^{-2}$. One Oklahoma producer, featured in a popular article (Hackett, 1999), planted early and at low populations; thus, relying on the sorghum hybrid to adapt to the growing conditions by tillering. Research by Jones and Johnson (1991, 1997) demonstrated that the optimum planting date, population, variety, and row spacing were interdependent. That is, late maturing varieties performed best when planted early and at lower populations; but, when soil water delayed planting, early maturing varieties planted at high populations in narrow rows increased grain yield. Furthermore, annual variability in growing season conditions also greatly limits application of field tests to identify optimum planting date, population, cultivar maturity, and row spacing combinations.

Weather variability at Bushland, TX, for example, growing season duration that ranges from 144 to 220 d around a 180-d mean, may easily bias short duration trials comparing planting date or cultivar maturity effects on grain yield. Similarly, highly variable precipitation that ranges from 89 to 580 mm around a 335-mm mean complicates evaluation of cultural practices in semiarid regions. One method to include this climatic variability and expand the basis for comparing cultural practices used in producing grain sorghum is using computer models to simulate crop growth and yields under recorded weather conditions. The grain sorghum computer simulation model SORKAM (Rosenthal et al., 1989) offers a standardized and economical means to compare multiple cropping practice combinations. Rosenthal and Gerik (1990) used SORKAM to compare the effects of cultivar maturity, planting date, and population on sorghum grain yield at eight Texas locations from Amarillo to Weslaco. The uniform planting populations and dates they used were not appropriate for all locations, but applying the model in this way did identify potentially successful management practices. This approach was also used in Kansas to identify criteria for replanting sorghum injured by storms after the normal or optimum planting date (Heiniger et al., 1997b). Similarly, SORKAM may be used to identify potentially optimum planting date, population, and row spacing combinations that maximize grain yield of select cultivars grown under dryland conditions on the southern Great Plains.

To meet this goal, our study objective was, first, to validate SORKAM yield simulations by comparing measured grain sorghum yield with simulated yields for selected years where the measured initial soil water content, known planting conditions, and corresponding weather data were available. We subsequently simulated growth and grain yield of early, medium, and late matur-

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Published in Agron. J. 97:935–942 (2005).
doi:10.2134/agronj2004.0087


**Abbreviations:** CM, cultivar maturity; D, planting date; HI, harvest index (kg $kg^{-1}$); P, plant population; RW, row width; SM, seed mass (mg $seed^{-1}$).

ing sorghum cultivars for all combinations of selected planting dates, row spacing, and plant populations for each year of the historical (1958–1998) weather record at Bushland, TX, to identify those cultural practices that optimize sorghum grain yield.

## MATERIALS AND METHODS

We simulated grain sorghum growth and yield using SORKAM version 2000 (W.D. Rosenthal and R.L. Vanderlip, personal communication, 2000), which is similar to the SORKAM version 1.1 described by Heiniger et al. (1997a) with a modified user interface and weather input. Crop simulations were conducted using the long-term (1958–1998) weather records from the USDA–Agricultural Research Service, Conservation and Production Research Laboratory, Bushland, TX, USA (35°11′ N lat; 102°5′ W long; and 1170 m asl). The laboratory weather records included daily solar irradiance (MJ $m^{-2}$), the maximum and minimum air temperature (°C), and precipitation (mm). The soil was a 1.8-m deep Pullman clay loam divided into nine layers with the available water and total porosity as shown in Fig. 1 (Howell et al., 1989; Steiner, 1989). Simulations were initiated with ~200 mm available soil water profile, which is typically present after fallow when using no-tillage residue management with a wheat (*Triticum aestivum* L.)–sorghum–fallow rotation (Jones and Popham, 1997). Maximum rooting depth, however, was 1.2 m as reported by Unger and Wiese (1979) for sorghum grown under dryland conditions. Soil water evaporation was calculated by the Priestley-Taylor method with an overall 1.45 scale factor, after Howell et al. (1989), using constants of 0.19 for albedo (Howell et al., 1989), 9.9 mm for U (Stage 1), and 7.8 mm $d^{-1}$ for C (Stage 2), the two stages of soil water evaporation as reported by Steiner (1989). Runoff was calculated using the measured NRCS curve number of 82 for sorghum reported by Hauser and Jones (1991). Because SORKAM simulates sorghum growth and yield for non limited nutrient conditions, soil fertility was necessarily assumed to be adequate for all simulations. Dryland cropping systems at Bushland, TX, mineralize about 50 kg N $ha^{-1}$ N (Eck and Jones, 1992) during fallow, which is adequate to meet sorghum needs for the expected dryland yields without supplemental N fertilization (Jones et al., 1997). The Pullman clay mineralogy supplies sufficient K to diminish crop response to fertilizer K (Johnson et al., 1983) and this calcareous soil reacts with P fertilizer and limits crop benefits (Eck, 1988). All simulations began 2 wk before planting and continued until a killing freeze or physiological maturity when grain yield was determined.

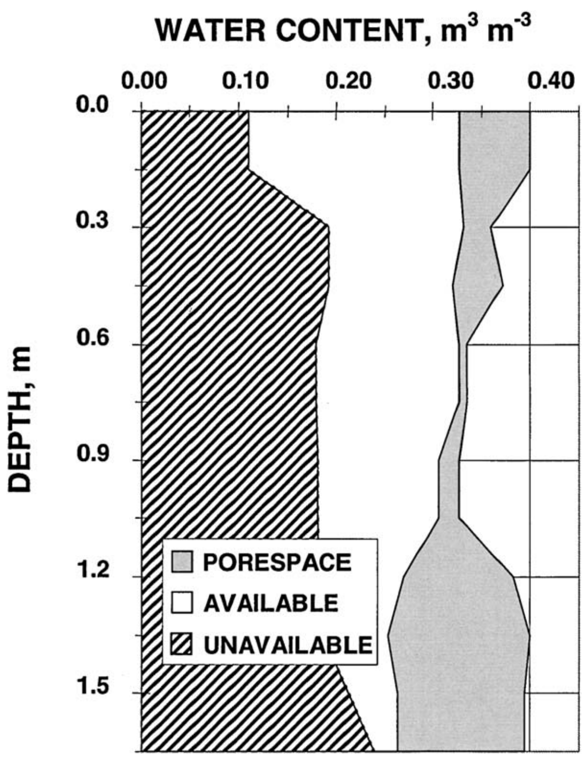


**Fig. 1. The Pullman soil used to simulate sorghum growth and yield extends to a depth of 1.83 m with unavailable water contents, hashed area, varying from 0.11 to 0.24 $m^3\ m^{-3}$ and available water contents, white area, that range from 0.26 to 0.33 $m^3\ m^{-3}$ (Howell et al., 1989; Steiner, 1989). Potential water-filled pore space was calculated from measured bulk density assuming 2.65 Mg $m^{-3}$ particle density.**

### Crop Simulations

Grain sorghum growth and yield was simulated for all possible combinations of selected cultivar maturities (three levels), planting dates (three levels), populations (three levels), and row widths (two levels). We tested three generic cultivar maturity classes that included early (15-leaf), medium (17-leaf), and late (19-leaf) maturing entries, which correspond to ~95, 105, and 120 d to reach maturity. Growth and yields of these cultivars were simulated under narrow (0.38 m) and conventional row widths (0.76 m) planted at low, medium, and high populations (3, 6, and 12 plants $m^{-2}$) on planting dates of 15 May (early), 5 June (normal), and 25 June (late). The 54 combinations of cultural practices were simulated for each of the 41 yr of actual weather conditions resulting in a total of 2214 simulations. The SORKAM simulated parameters of plant grain and biomass yields, plant tillers, seed number per panicle, and mean seed weight were evaluated.

To validate SORKAM, we compared measured grain yield observations from medium (17-leaf) and late (19-leaf) maturing cultivars grown from 1984 to 1998 with simulated grain yields. The measured sorghum yields were taken from no-tillage residue management plots within the wheat–sorghum–fallow rotation study described by Jones and Popham (1997). This was because of more reliable and timely experimental crop establishment in soil that had better "planting moisture" and, consequently, an increased number of validation comparisons. The SORKAM yields were simulated using the corresponding observed weather, measured soil water content at planting, and the experimental planting date, row width, and plant population conditions as input data.

### Analyses

The grain sorghum growth and yield values simulated with SORKAM were treated as experimental observations in which replication was provided by years. Descriptive univariate statistics and Pearson correlation were determined for the treatment cultural practices, recorded growing season precipitation, and all simulated growth parameters to identify correlated parameters (SAS Inst., 1988). We compared the SORKAM simulated grain yield and growth values according to a factorial arrangement of the cultural practice treatments using the SAS general linear models ANOVA procedures. Correlation of growing season length and precipitation with the planting date treatment ($r^2 = 0.39$) precluded using the precipitation data as a covariant in subsequent analyses.

## RESULTS AND DISCUSSION

### Validation

The accuracy of SORKAM simulated grain sorghum growth and yield was previously established by Rosenthal and Gerik (1990), Heiniger et al. (1997a), and others. However, we also validated SORKAM by comparing measured experimental yields with the corresponding simulated grain yields for late (19-leaf) and medium (17-leaf) maturity cultivars. Our validation of SORKAM was based on grain yield data observed under unique plant population and row spacing conditions that were not included in any other analyses. Simulated grain yields, shown in Fig. 2, ranged from 1310 to 7110 kg ha$^{-1}$ with a mean of 4035 kg ha$^{-1}$ that was ~5% greater than the analogous mean measured experimental yield of 3830 kg ha$^{-1}$ (range 1210 to 6460 kg ha$^{-1}$), with a $r^2 = 0.69$ (RMSE = 792 kg ha$^{-1}$) obtained during the 15-yr period. These differences are expected because the model does not consider the impact of common biotic pressures such as weed competition, insect injury, soil fertility or planting moisture effects on emergence and stand uniformity when simulating crop growth and yield. Tolk et al. (2003) compared SORKAM simulated grain yields with independent experimental grain yields obtained for row widths of 0.38 or 0.76 m, and populations of 3.1, 6.5, and 13.0 plants m$^{-2}$. Although simulated grain yield values were consistently 80 to 90% of the experimental grain sorghum yields, SORKAM reproduced the measured row width and population effects on grain yield and water use.

The SORKAM simulated crop growth and grain yields accurately reflected measured crop performance throughout a broad range of environmental conditions and tested cultural practices. This suggests that the SORKAM simulated grain yields will reflect the impact of the tested planting conditions on sorghum growth and grain yield.

### Grain Yield and Yield Factors

The SORKAM-simulated dryland sorghum grain yields for 1958–1998 ranged from 0 to 8905 kg ha$^{-1}$ and averaged 4069 kg ha$^{-1}$ across all planting dates, populations, cultivar maturities, and row spacing combinations. The broad range in grain yield reflects the erratic precipitation (from 89 to 580 mm) and growing season length (from 144 to 220 d) that is characteristic of the semiarid southern Great Plains weather. For example, the long-term average fall freeze date at Bushland is 22 October, but varied from 21 September to 14 November during 1958–1998. The growing season precipitation was significantly correlated with simulated grain yield ($r = 0.61$, $P < 0.001$); however, precipitation was not included as a covariant in subsequent analyses because of its correlation with the planting date treatment class.

Simulated grain yields listed in Table 1 also varied significantly ($P < 0.001$) with cultivar maturity effects that were independent of the other treatments. Based on simulated crop yields for the years 1958–1998, the

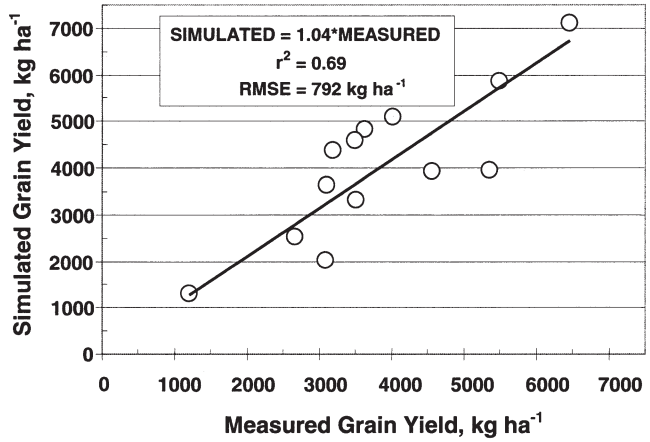


**Fig. 2. Sorghum grain yields simulated using SORKAM with known planting conditions and recorded precipitation plotted in comparison with the corresponding measured experimental grain yields from 1984 to 1998.**

3860 kg ha$^{-1}$ yield mean for late maturing sorghum was significantly less than yields of either the early or medium maturity cultivars that produced 4250 and 4100 kg ha$^{-1}$ grain, respectively. Although later maturing cultivars have the potential to increase grain yield because of their longer growing season, under dryland conditions the extended growing season increases exposure to days with yield limiting water-deficit conditions and the potential for freeze injury. One-third of the simulated yields for late maturing cultivars were from plants that did not reach physiological maturity (data not shown) in contrast with 16 and 5% for medium and early maturing cultivars. Late maturing cultivars do not appear to be well suited for dryland cropping practices on much of the southern High Plains where the growing season averages approximately 185 d or less.

Simulated sorghum grain yields also varied significantly in response to row width, and planting date, but not to population levels, averaging from 4000 to 4110 kg ha$^{-1}$. Overall sorghum grain yield for narrow row-spacing (0.38 m) averaged 4240 kg ha$^{-1}$ or about 9% greater than the mean 3900 kg ha$^{-1}$ grain yield with wider row-spacing (0.76 m). For fixed plant populations, reducing the distance between rows, consequently, distributes plants more evenly within the field and decreases early season competition between plants, thereby improving light interception and partitioning of soil–water for use in evapotranspiration as reported for field measurements by Steiner (1986). Implementing this narrow row spacing cultural practice would require a relatively simple modification of equipment. Another easily modified cultural practice is the crop planting date; however, any variation of the planting date must strike a balance between extending the potential growing season and exposing the crop to late summer heat and water deficit or fall freeze risks. Under our test conditions, the overall simulated grain yield averaged 4295 kg ha$^{-1}$ for the 5 June planting date and was significantly greater than mean grain yields of 4040 kg ha$^{-1}$ for 25 June and 3870 kg ha$^{-1}$ or 15 May dates. Compared with the 5 June planting date, earlier planted sorghum matured during

**Table 1. Simulated grain yield ± the standard error listed by planting date (D), population (P), and row width (RW) main treatment effects within cultivar maturity class (C). The corresponding ANOVA results designate significance level ($P > F$) of treatment effects.**

| Planting date | Row width, cm | Early maturity 38 | Early maturity 76 | Medium maturity 38 | Medium maturity 76 | Late maturity 38 | Late maturity 76 |
|---|---|---|---|---|---|---|---|
| | population, plants m$^{-2}$ | grain yield, kg ha$^{-1}$ | | | | | |
| 15 May | 3 | 4116 ± 180 | 3886 ± 167 | 4206 ± 285 | 3898 ± 270 | 4071 ± 324 | 3750 ± 302 |
| | 6 | 4299 ± 269 | 4008 ± 248 | 3920 ± 331 | 3666 ± 306 | 3860 ± 374 | 3506 ± 337 |
| | 12 | 4162 ± 311 | 3894 ± 297 | 3857 ± 364 | 3454 ± 337 | 3772 ± 395 | 3374 ± 369 |
| 5 June | 3 | 4409 ± 155 | 4155 ± 144 | 4586 ± 266 | 4243 ± 245 | 4432 ± 326 | 4081 ± 296 |
| | 6 | 4682 ± 248 | 4352 ± 225 | 4521 ± 315 | 4165 ± 298 | 4434 ± 374 | 3940 ± 350 |
| | 12 | 4613 ± 292 | 4331 ± 279 | 4396 ± 363 | 3958 ± 344 | 4183 ± 411 | 3827 ± 390 |
| 25 June | 3 | 4197 ± 129 | 3950 ± 118 | 4299 ± 228 | 3961 ± 215 | 4008 ± 252 | 3644 ± 232 |
| | 6 | 4504 ± 212 | 4162 ± 190 | 4398 ± 275 | 3969 ± 258 | 3968 ± 338 | 3549 ± 312 |
| | 12 | 4518 ± 265 | 4221 ± 251 | 4348 ± 336 | 3943 ± 322 | 3677 ± 387 | 3397 ± 369 |

| Effect | df | $P > F$ |
|---|---|---|
| Cultivar (C) | 2 | <0.001 |
| Row width (RW) | 1 | <0.001 |
| Population (P) | 2 | 0.437 |
| Planting date (D) | 2 | <0.001 |
| C × RW | 2 | 0.883 |
| C × P | 4 | 0.334 |
| C × D | 4 | 0.614 |
| RW × P | 2 | 0.956 |
| RW × D | 2 | 0.976 |
| P × D | 4 | 0.950 |
| C × RW × P | 4 | 0.999 |
| C × RW × D | 4 | >0.999 |
| C × P × D | 8 | >0.999 |
| RW × P × D | 4 | 0.999 |
| C × RW × P × D | 8 | >0.999 |

late summer water deficit stress, which decreased grain yield. Sorghum planted 25 June failed to reach physiological maturity because of freezing fall temperatures during 61% of the simulated growing seasons and, consequently, the growing seasons were insufficient for the crop to achieve its potential yield under the prevailing conditions.

Grain sorghum adapts to the prevailing growing conditions by adjusting the number of seed heads through tillering. Simulated tiller initiation was significantly ($P <$ 0.001) greater with later cultivar maturity that increased from 1.13 tillers plant$^{-1}$ for early maturing cultivars to 1.56 tillers plant$^{-1}$ for medium maturing cultivars and 1.74 tillers plant$^{-1}$ for late maturing cultivars (Table 2). These results suggest that planting early maturing cultivars decreases tillering and allows greater control of seed head numbers under dryland conditions. As the initial plant population increased, mean tiller number also decreased from 1.82 with the low population to overall means of 1.47 and 1.13 for the medium and high plant populations, respectively. For constant plant populations, increasing the row width from 0.38 to 0.76 m increased the in-row plant density and, as simulated for increasing populations, the corresponding mean tiller number decreased from 1.57 to 1.38. Our simulations show that increasing in-row plant density by varying row spacing ($r = -0.20$, $P < 0.01$) or plant population ($r = -0.58$, $P < 0.01$) significantly decreased tiller numbers and were consistent with field measurements by Jones and Johnson (1991) and Staggenborg et al. (1999). That is, cultural practices used to increase in-row plant density may also suppress tiller number possibly because of competition among plants for nutrients or because of increased light interception with higher populations (Lafarge et al., 2002). Longer days and more direct illumination of sorghum plants with the progressively later planting dates may have increased tillering resulting in a gradual increase from 1.38 plant tillers for the early 15 May planting date to 1.47 plant tillers for 5 June and 1.57 plant tillers for the late 25 June planting dates. Although greater plant tillering increases yield potential by increasing the number of seed heads, this benefit may be offset somewhat by an increased use of soil water and nutrient resources to produce the supporting leaf and stem structure for each additional tiller head as indicated by Jones and Johnson (1991). Nevertheless, simulated plant tiller number were weakly correlated to grain yield ($r = 0.07$, $P < 0.01$). Future research may determine if cultural practices that limit plant tillers concomitantly increase harvest index and water use efficiency, which is especially important under limited water conditions of dryland cropping systems.

Another indicator of grain sorghum production efficiency is the harvest index (HI) listed in Table 3, which is the dry grain yield divided by the total aboveground plant biomass. As observed for increased tillering with progressively later maturing cultivars, the mean simulated HI decreased significantly ($P < 0.001$) as cultivar maturity decreased from a high HI of 0.46 with early maturing cultivars to HI of 0.40 and 0.35 for the medium and late maturing cultivars. Our simulated mean HI was consistently smaller for narrow rows ($P = 0.018$), and decreased significantly from 0.43 with the low population to 0.41 and 0.38 for the medium and high plant populations. The HI often decreases as growing conditions favorable to rapid plant growth are followed by water deficit stress conditions that fail to support subsequent grain production and filling. For example, Lafarge et al. (2002) reported that the number of nongrain producing, infertile, tillers increased with increased plant

**Table 2. Simulated plant tillers ± the standard error listed by planting date (D), population (P), and row width (RW) main treatment effects within cultivar maturity class (C). The corresponding ANOVA results designate significance level ($P > F$) of treatment effects.**

| | | Early maturity | | Medium maturity | | Late maturity | |
|---|---|---|---|---|---|---|---|
| Planting date | Row width, cm | 38 | 76 | 38 | 76 | 38 | 76 |
| | population, plants $m^{-2}$ | tillers $plant^{-1}$ | | | | | |
| 15 May | 3 | 1.20 ± 0.04 | 1.18 ± 0.04 | 1.87 ± 0.05 | 1.72 ± 0.04 | 2.21 ± 0.06 | 1.93 ± 0.05 |
| | 6 | 1.11 ± 0.03 | 1.00 ± 0.03 | 1.58 ± 0.04 | 1.36 ± 0.03 | 1.75 ± 0.05 | 1.49 ± 0.04 |
| | 12 | 0.93 ± 0.03 | 0.81 ± 0.02 | 1.22 ± 0.03 | 1.05 ± 0.02 | 1.32 ± 0.03 | 1.14 ± 0.03 |
| 5 June | 3 | 1.35 ± 0.03 | 1.32 ± 0.03 | 2.03 ± 0.06 | 1.82 ± 0.05 | 2.38 ± 0.06 | 2.04 ± 0.05 |
| | 6 | 1.23 ± 0.02 | 1.10 ± 0.02 | 1.66 ± 0.04 | 1.42 ± 0.04 | 1.84 ± 0.04 | 1.55 ± 0.04 |
| | 12 | 0.99 ± 0.02 | 0.87 ± 0.02 | 1.27 ± 0.03 | 1.10 ± 0.03 | 1.36 ± 0.03 | 1.18 ± 0.03 |
| 25 June | 3 | 1.45 ± 0.03 | 1.40 ± 0.03 | 2.19 ± 0.05 | 1.96 ± 0.04 | 2.57 ± 0.05 | 2.19 ± 0.04 |
| | 6 | 1.30 ± 0.03 | 1.14 ± 0.02 | 1.78 ± 0.04 | 1.51 ± 0.03 | 1.97 ± 0.04 | 1.65 ± 0.03 |
| | 12 | 1.05 ± 0.02 | 0.91 ± 0.02 | 1.34 ± 0.03 | 1.15 ± 0.02 | 1.45 ± 0.03 | 1.25 ± 0.02 |

| Effect | df | $P > F$ |
|---|---|---|
| Cultivar (C) | 2 | <0.001 |
| Row width (RW) | 1 | <0.001 |
| Population (P) | 2 | <0.001 |
| Planting date (D) | 2 | <0.001 |
| C × RW | 2 | <0.001 |
| C × P | 4 | <0.001 |
| C × D | 4 | 0.378 |
| RW × P | 2 | 0.051 |
| RW × D | 2 | 0.158 |
| P × D | 4 | <0.001 |
| C × RW × P | 4 | 0.003 |
| C × RW × D | 4 | 0.994 |
| C × P × D | 8 | 0.997 |
| RW × P × D | 4 | 0.941 |
| C × RW × P × D | 8 | >0.999 |

density and, consequently, HI decreased. Progressively later maturing varieties and planting dates increased the risk that physiological maturity and optimum grain yield are not achieved and, consequently, HI decreases. Simulated HI averaged 0.42 for 5 June planting compared with the significantly smaller mean HI of 0.40 and 0.39 simulated for the 25 June and 15 May planting. Our simulation results suggest those management practices that reduce tillering also tend to reduce excess biomass production and, therefore, increase the grain sorghum HI.

## Sorghum Stress Indicators

Using multiple regression analysis, Krieg and Lascano (1990) related dryland sorghum grain yield to the primary yield components of panicle number ($R^2 = 0.12$), number of seeds per panicle ($R^2 = 0.57$), and seed

**Table 3. Simulated harvest index ± the standard error listed by planting date (D), population (P), and row width (RW) main treatment effects within cultivar maturity class (C). The corresponding ANOVA results designate significance level ($P > F$) of treatment effects.**

| | | Early maturity | | Medium maturity | | Late maturity | |
|---|---|---|---|---|---|---|---|
| Planting date | Row width, cm | 38 | 76 | 38 | 76 | 38 | 76 |
| | population, plants $m^{-2}$ | harvest index, kg $kg^{-1}$ | | | | | |
| 15 May | 3 | 0.47 ± 0.01 | 0.47 ± 0.01 | 0.42 ± 0.01 | 0.43 ± 0.01 | 0.38 ± 0.02 | 0.39 ± 0.02 |
| | 6 | 0.44 ± 0.01 | 0.45 ± 0.01 | 0.38 ± 0.02 | 0.40 ± 0.02 | 0.33 ± 0.02 | 0.35 ± 0.02 |
| | 12 | 0.41 ± 0.02 | 0.44 ± 0.02 | 0.35 ± 0.02 | 0.35 ± 0.02 | 0.31 ± 0.03 | 0.32 ± 0.03 |
| 5 June | 3 | 0.48 ± 0.01 | 0.48 ± 0.01 | 0.44 ± 0.01 | 0.45 ± 0.01 | 0.39 ± 0.02 | 0.41 ± 0.02 |
| | 6 | 0.46 ± 0.01 | 0.47 ± 0.01 | 0.41 ± 0.01 | 0.43 ± 0.01 | 0.37 ± 0.02 | 0.38 ± 0.02 |
| | 12 | 0.45 ± 0.01 | 0.45 ± 0.01 | 0.38 ± 0.02 | 0.39 ± 0.02 | 0.33 ± 0.02 | 0.34 ± 0.02 |
| 25 June | 3 | 0.47 ± 0.01 | 0.48 ± 0.01 | 0.42 ± 0.01 | 0.43 ± 0.01 | 0.37 ± 0.01 | 0.39 ± 0.01 |
| | 6 | 0.46 ± 0.01 | 0.47 ± 0.01 | 0.41 ± 0.01 | 0.42 ± 0.01 | 0.33 ± 0.02 | 0.34 ± 0.02 |
| | 12 | 0.45 ± 0.01 | 0.46 ± 0.01 | 0.38 ± 0.02 | 0.39 ± 0.02 | 0.29 ± 0.03 | 0.30 ± 0.03 |

| Effect | df | $P > F$ |
|---|---|---|
| Cultivar (C) | 2 | <0.001 |
| Row width (RW) | 1 | 0.018 |
| Population (P) | 2 | <0.001 |
| Planting date (D) | 2 | 0.001 |
| C × RW | 2 | 0.963 |
| C × P | 4 | 0.043 |
| C × D | 4 | 0.085 |
| RW × P | 2 | 0.926 |
| RW × D | 2 | 0.989 |
| P × D | 4 | 0.879 |
| C × RW × P | 4 | 0.949 |
| C × RW × D | 4 | 0.999 |
| C × P × D | 8 | 0.938 |
| RW × P × D | 4 | 0.998 |
| C × RW × P × D | 8 | >0.999 |

**Table 4. Simulated panicle seed number ± the standard error listed by planting date (D), population (P), and row width (RW) main treatment effects within cultivar maturity class (C). The corresponding ANOVA results designate significance level ($P > F$) of treatment effects.**

| | | Early maturity | | Medium maturity | | Late maturity | |
|---|---|---|---|---|---|---|---|
| **Planting date** | **Row width, cm** | **38** | **76** | **38** | **76** | **38** | **76** |
| | **population, plants m$^{-2}$** | **seed mass, mg** | | | | | |
| **15 May** | **3** | **5216 ± 114** | **4699 ± 106** | **3841 ± 145** | **3619 ± 136** | **3185 ± 198** | **3120 ± 193** |
| | **6** | **3278 ± 107** | **3146 ± 99** | **2308 ± 147** | **2364 ± 137** | **2048 ± 158** | **2138 ± 160** |
| | **12** | **2036 ± 107** | **2098 ± 93** | **1490 ± 120** | **1499 ± 126** | **1340 ± 120** | **1367 ± 125** |
| **5 June** | **3** | **4779 ± 99** | **4353 ± 90** | **3674 ± 120** | **3558 ± 115** | **3094 ± 152** | **3141 ± 151** |
| | **6** | **3034 ± 80** | **2989 ± 78** | **2401 ± 109** | **2459 ± 109** | **2051 ± 134** | **2105 ± 141** |
| | **12** | **2025 ± 79** | **2056 ± 78** | **1572 ± 99** | **1611 ± 104** | **1345 ± 103** | **1391 ± 110** |
| **25 June** | **3** | **4264 ± 89** | **3913 ± 77** | **3173 ± 71** | **3108 ± 66** | **2623 ± 82** | **2678 ± 81** |
| | **6** | **2777 ± 62** | **2752 ± 55** | **2071 ± 68** | **2147 ± 69** | **1670 ± 105** | **1733 ± 112** |
| | **12** | **1828 ± 51** | **1877 ± 50** | **1339 ± 73** | **1379 ± 79** | **1056 ± 91** | **1104 ± 97** |

| **Effect** | **df** | $P > F$ |
|---|---|---|
| **Cultivar (C)** | **2** | **<0.001** |
| **Row width (RW)** | **1** | **0.172** |
| **Population (P)** | **2** | **<0.001** |
| **Planting date (D)** | **2** | **<0.001** |
| **C × RW** | **2** | **0.029** |
| **C × P** | **4** | **<0.001** |
| **C × D** | **4** | **0.073** |
| **RW × P** | **2** | **0.004** |
| **RW × D** | **2** | **0.675** |
| **P × D** | **4** | **<0.001** |
| **C × RW × P** | **4** | **0.145** |
| **C × RW × D** | **4** | **0.999** |
| **C × P × D** | **8** | **0.786** |
| **RW × P × D** | **4** | **0.953** |
| **C × RW × P × D** | **8** | **>0.999** |

mass, mg ($R^2 = 0.12$). In their review article, they noted that the number of seeds per panicle was determined by environmental conditions, such as the degree of water stress imposed on a plant, from panicle initiation to flowering (anthesis). Additionally, seed mass was affected by post anthesis stress conditions including water deficits or an early freeze. In our test, we compared both simulated panicle seed number and mass of seed as a means to identify management practices that would minimize growing stress conditions.

Simulated panicle seed number is listed in Table 4 together with ANOVA results. Mean panicle seed number increased significantly ($P < 0.001$) from 2070 for the late maturing cultivar to 2420 for the medium and 3170 for the early maturing cultivars. We attributed this to an increasingly shorter period between planting and panicle initiation with earlier maturing cultivars that, consequently, limited plant exposure to any water deficit stress. Panicle seed number was unaffected by decreased row width that increased spatial distribution of plants and decreased seedling competition except for the increased seed number obtained with early maturing cultivars. Simulated panicle seed number decreased as the combined effect of tiller number and population increased the overall panicle number, i.e., seed number was negatively correlated to panicle number ($r = -0.78$, $P < 0.001$). Plant tillering alone was not correlated to seed number ($r = 0.05$) because sorghum usually tillers to offset low plant populations. Panicle seed number decreased dramatically from an average of 3670 at the low populations to averages of 2415 at medium populations and 1580 at the high populations [LSD(0.05) = 72.5]. This is attributed to greater competition for water among plants that apparently depressed seed formation during panicle initiation. Seed number decreased progressively with delayed planting, which extended later into the hotter and dryer summer, for example, simulated seed number for 15 May and 5 June planting dates averaged 2710 and 2650 compared with the significantly lower 2305 mean seed number simulated for the 25 June planting date. Potentially greater water deficit and temperature stresses occurred with later planting dates, which impacted the sorghum plant during the critical seed differentiation period. These results show that management practices such as reduced planting populations can limit competition among plants and avoid exposing the crop to potential environmental, water deficit, and stress conditions early in the growing season, thus increasing seed number and grain yield potential.

The simulated seed mass and corresponding ANOVA results are listed by treatment effects in Table 5. Our results indicate that seed mass steadily increased from an average of 17.9 mg for late maturing cultivars to 19.3 and 21.6 mg for the medium and early maturing cultivars [LSD(0.05) = 0.7 mg]. Seed mass of early maturing cultivars also benefited significantly from narrow row width and decreased significantly with increasing plant populations and progressively earlier maturing cultivars. For example, mean seed mass increased from 17.9 mg for the high-population to mean seed masses of 19.4 and 21.5 mg for the medium and low population densities. Physiological maturity was delayed with increasing populations and later maturing cultivars, which increased freeze injury and depressed grain yield. That is, 32% of crop simulations for late maturing varieties failed to reach physiological maturity compared with 16 and 5% for medium and early maturing varieties. Alternatively, post anthesis water deficit stress decreased seed mass

**Table 5. Simulated seed mass, mg, ± the standard error listed by planting date (D), population (P), and row width (RW) main treatment effects within cultivar maturity class (C). The corresponding ANOVA results are reported by cultivar maturity and designate significance level ($P > F$) of treatment effects.**

| | | Early maturity | | Medium maturity | | Late maturity | |
|---|---|---|---|---|---|---|---|
| Planting date | Row width, cm | 38 | 76 | 38 | 76 | 38 | 76 |
| | population, plants m$^{-2}$ | seed mass, mg | | | | | |
| 15 May | 3 | 22.8 ± 0.9 | 24.2 ± 0.9 | 19.6 ± 1.0 | 20.8 ± 1.1 | 18.9 ± 1.0 | 20.1 ± 1.1 |
| | 6 | 20.1 ± 1.0 | 21.5 ± 1.1 | 17.5 ± 0.9 | 18.8 ± 1.0 | 16.4 ± 1.2 | 16.9 ± 1.2 |
| | 12 | 17.9 ± 0.9 | 19.0 ± 1.0 | 16.9 ± 1.1 | 17.4 ± 1.2 | 15.9 ± 1.2 | 16.0 ± 1.3 |
| 5 June | 3 | 23.4 ± 0.7 | 24.7 ± 0.8 | 20.7 ± 0.9 | 22.0 ± 0.9 | 19.3 ± 1.0 | 20.6 ± 1.0 |
| | 6 | 21.0 ± 0.9 | 22.3 ± 1.0 | 18.9 ± 0.8 | 19.8 ± 0.9 | 18.2 ± 1.1 | 18.5 ± 1.2 |
| | 12 | 19.2 ± 0.9 | 20.2 ± 1.0 | 17.5 ± 1.0 | 17.7 ± 1.0 | 16.6 ± 1.2 | 16.9 ± 1.2 |
| 25 June | 3 | 23.5 ± 0.7 | 24.7 ± 0.7 | 20.7 ± 0.9 | 21.7 ± 0.9 | 19.4 ± 0.8 | 20.2 ± 0.8 |
| | 6 | 21.3 ± 0.9 | 22.4 ± 0.9 | 19.6 ± 0.8 | 20.0 ± 0.9 | 17.8 ± 1.2 | 18.1 ± 1.2 |
| | 12 | 19.6 ± 0.9 | 20.5 ± 1.0 | 19.0 ± 0.9 | 19.3 ± 1.0 | 15.9 ± 1.3 | 16.1 ± 1.4 |

| Effect | df | $P > F$ |
|---|---|---|
| Cultivar (C) | 2 | <0.001 |
| Row width (RW) | 1 | 0.002 |
| Population (P) | 2 | <0.001 |
| Planting date (D) | 2 | 0.003 |
| C × RW | 2 | 0.621 |
| C × P | 4 | 0.463 |
| C × D | 4 | 0.718 |
| RW × P | 2 | 0.612 |
| RW × D | 2 | 0.933 |
| P × D | 4 | 0.891 |
| C × RW × P | 4 | 0.996 |
| C × RW × D | 4 | >0.999 |
| C × P × D | 8 | 0.978 |
| RW × P × D | 4 | >0.999 |
| C × RW × P × D | 8 | >0.999 |

where physiological maturity was achieved. The simulated seed mass for the 15 May planting date averaged 18.9 mg and was significantly lower than the mean seed mass of 19.9 and 20.0 mg simulated for the 5 June and 25 June planting dates, respectively. In this case, the earlier planted sorghum generally reached post-anthesis growing stages during the hottest summer months and likely suffered from greater water deficit stress compared with later planted sorghum. Seed mass depends on many interacting factors that affect grain fill including, for example, the seed number ($r = 0.49$, $P < 0.001$) established during the early preanthesis growing season and also plant dry matter accumulation ($r = 0.64$, $P < 0.001$) that was often limited by late summer water deficit stress.

Relying on seed number and mass to identify management practices that limited the simulated crop growth and grain yield, we determined that high planting populations and late maturing cultivars should be avoided. Under dryland conditions, the lower plant populations and earlier maturing cultivars produced more seed panicle$^{-1}$, were exposed to less post-anthesis water deficit stress, and achieved greater grain yield potential.

## SUMMARY AND CONCLUSIONS

For known cultural practices and recorded seasonal growing conditions we used the SORKAM crop growth model to simulate grain sorghum yields, which were validated against measured grain yield. In our validation row width, population and cultivar maturity were varied. Using long-term weather records and the SORKAM model, we then simulated dryland sorghum growth and grain yield for various cultural practices. Compared with 0.76-m row spacing, narrow rows (0.38 m) increased tillering, seed mass, and grain yield by expanding the spatial plant distribution and decreasing competition for water, nutrients, and light. Higher plant populations decreased simulated panicle seed number, seed mass, and tiller number, which was similar to field tests by Staggenborg et al. (1999) and Jones and Johnson (1991). The increased seed number and mass with decreasing plant population was offset, however, by the panicle number (population × tiller) that varied inversely with population and neutralized any grain yield benefit. Optimum simulated grain yield was obtained for a 5 June planting date compared with the early 15 May or late 25 June dates. Early planted sorghum developed more seed per panicle and fewer panicles per plant, but seed mass was significantly smaller, probably because of greater late summer post-anthesis water deficit stress. Except for early maturing cultivars, late planted sorghum frequently failed to reach physiological maturity.

From this study we conclude that narrow row spacing increases dryland grain sorghum yield. We identified cultural practices that increased sorghum grain yield and minimized dryland risk, such as decreasing water deficit stress duration by using early maturing cultivars planted at low or medium populations. Early planting dates did not extend or beneficially shift the growing season to improve use of precipitation or increase grain yield. However, late planting dates increased the risk that sorghum would not reach physiological maturity and reduced grain yield. We conclude that early or medium maturity cultivars, planted 5 June, in 0.38 m row widths, using 3 or 6 plants m$^{-2}$ populations, have the largest yield potential for the southern High Plains on a clay loam soil.

## ACKNOWLEDGMENTS

Partial funding of this work from the "Productive Rotations on Farms in Texas—PROFIT" research initiative, "High Plains Cropping Systems," regional project (no. 12-9901) is gratefully acknowledged.

## REFERENCES

Eck, H.V. 1988. Winter wheat response to nitrogen and irrigation. Agron. J. 80:902–908.

Eck, H.V., and O.R. Jones. 1992. Soil nitrogen status as affected by tillage, crops, and crop sequences. Agron. J. 84:660–668.

Hackett, T. 1999. Dietrick drops 'Cast-Iron Farming' before it's too late. Natl. Conserv. Tillage Digest 6(2):4–7.

Hauser, V.L., and O.R. Jones. 1991. Runoff curve numbers for the Southern High Plains. Trans. ASAE 34:142–148.

Heiniger, R.W., R.L. Vanderlip, S.M. Welch, and R.C. Muchow. 1997a. Developing guidelines for replanting grain sorghum: II. Improved methods of simulating caryopsis weight and tiller number. Agron. J. 89:84–92.

Heiniger, R.W., R.L. Vanderlip, J.R. Williams, and S.M. Welch. 1997b. Developing guidelines for replanting grain sorghum: III. Using a plant growth model to determine replanting options. Agron. J. 89: 93–100.

Howell, T.A., K.S. Copeland, A.D. Schneider, and D.A. Dusek. 1989. Sprinkler irrigation management for corn: Southern Great Plains. Trans. ASAE 32:147–154, 160.

Johnson, W.C., E.L. Skidmore, B.B. Tucker, and P.W. Unger. 1983. Soil conservation: Central Great Plains winter wheat and range region. p. 197–217. *In* H.E. Dregne and W.O. Willis (ed.) Dryland agriculture. Agron. Monogr. 23. ASA, Madison, WI.

Jones, O.R., and G.L. Johnson. 1991. Row width and plant density effects on Texas High Plains sorghum. J. Prod. Agric. 4:613–619.

Jones, O.R., and G.L. Johnson. 1997. Evaluation of a short season high density production strategy for dryland sorghum. AREC 97–01.

Jones, O.R., and T.W. Popham. 1997. Cropping and tillage systems for dryland grain production in the Southern High Plains. Agron. J. 89:222–232.

Jones, O.R., B.A. Stewart, and P.W. Unger. 1997. Management of dry-farmed southern Great Plains soils for sustained productivity. p. 387–401. *In* E.A. Paul et al. (ed.) Soil organic matter in temperate agroecosystems: Long-term experiments in North America. CRC Press, Boca Raton, FL.

Krieg, D.R., and R.J. Lascano. 1990. Sorghum. p. 719–739. *In* B.A. Stewart and D.R. Nielsen (ed.) Irrigation of agricultural crops. Agron. Monogr. 30. ASA, CSSA, and SSSA, Madison, WI.

Lafarge, T.A., I.J. Broad, and G.L. Hammer. 2002. Tillering in grain sorghum over a wide range of population densities: Identification of a common hierarchy of tiller emergence, leaf area development and fertility. Ann. Bot. 90:87–98.

Rosenthal, W.D., and T.J. Gerik. 1990. Application of a crop growth model to evaluate cultural practices and optimize dryland grain sorghum yield. J. Prod. Agric. 3:124–131.

Rosenthal, W.D., R.L. Vanderlip, G.F. Arkin, and B.S. Jackson. 1989. SORKAM: A grain sorghum crop growth model. Rep. MP-1699. Texas Agric. Exp. Stn.

SAS Institute. 1988. SAS/STAT users guide. Release 6.03 ed. SAS Inst., Cary, NC.

Staggenborg, S.A., D.L. Fjell, D.L. Devlin, W.B. Gordon, and B.H. Marsh. 1999. Grain sorghum response to row spacings and seeding rates in Kansas. J. Prod. Agric. 12:390–395.

Steiner, J.L. 1986. Dryland grain sorghum water use, light interception, and growth responses to planting geometry. Agron. J. 78:720–726.

Steiner, J.L. 1989. Tillage and surface residue effects on evaporation from soils. Soil Sci. Soc. Am. J. 53:911–916.

Tolk, J.A., R.L. Baumhardt, and T.A. Howell. 2003. Measured and simulated grain sorghum yield response to row spacing. *In* Annual meetings abstracts [CD-ROM]. ASA, CSSA, and SSSA, Madison, WI.

Unger, P.W., and R.L. Baumhardt. 1999. Factors related to dryland grain sorghum yield increases, 1939 through 1997. Agron. J. 91: 870–875.

Unger, P.W., and A.F. Wiese. 1979. Managing irrigated winter wheat residues for water storage and subsequent dryland grain sorghum production. Soil Sci. Soc. Am. J. 43:582–588.